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TECHNICAL REPORT RD-SS-90-6

HYDRA 70 MK66 AERODYNAMICS AND ROLL ANALYSIS

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Center

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U.S. ARMY MISSILE COMMAND
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This report is intended to complement, summarize, and update previous reports on the aerodynamic characteristics of the 2.75 family of rockets. It presents a more detailed basic aerodynamic characterization of the rocket with the two principal warheads that typify most of the configurations of the Hydra 70 system. The reason for publishing this report at this time is that recent studies have suggested application of the MK66 motor, or a derivative thereof, for future systems, and that a more detailed aerodynamic definition in one source may be useful.

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I. INTRODUCTION

The MARK66 (MK66) motor is used as the propulsion device for the multiplicity of HYDRA 70 warhead configurations and launch platforms. A recent report, Reference 1, has been prepared by Naval Ordnance Station Indian Head, MD, describing the MK66 motor mass and propulsive characteristics (see Tables 1 and 2). This report is intended to complement Reference 1 by presenting a more detailed basic aerodynamic characterization of the rocket with the two principal warheads that typify most of the configurations of the Hydra 70 system. Recently there have been several studies suggesting additional application of the MK66, or a derivative, for future systems where more detailed aerodynamic definition may be useful.

The MK66 motor was developed by the Navy through a product improvement program (PIP) for the MARK 40, 2.75-inch rocket system. The differences include a propellant with 30 percent more total impulse and reconfigured tail fins which provide better aerodynamic stabilization. The rocket nozzle assembly is similar to the Navy Zuni rocket configuration. The principal difference, besides scale, is three wraparound fins (WAF's) replacing the ZUNI four fin configuration. During early flight tests, the MK66 rocket with the original (MOD 0) Navy designed tail fin was observed to exhibit flight dynamic anomalies that resulted in shorter range than predicted.

In mid 1979, the Army 2.75 Management Office tasked the MICOM System Simulation and Development Directorate to assist in defining and solving the short range problem. A substantial data base for wraparound fin configurations had by this time been assembled through MICOM in-house aerodynamic technology studies. This data base was used to characterize MK66 configuration and subsequent flight simulations suggested that roll rate decayed or possibly reversed during flight.

The MK66 nozzle is fluted to produce roll torque, and boost roll rates were observed to exceed 50 Hz toward the end of boost at approximately one second. Aerodynamic roll moments were not adequately wind tunnel tested for both MK66 and ZUNI. Prior to the 1970's, many aerodynamic designers had avoided considering the WAF because of their unusual aerodynamic roll moment characteristics. ZUNI was designed and developed for short range air-to-surface application where significant range beyond end of boost was not required. Additionally, ZUNI is expected to exhibit wobble during long range flights in a surface-to-surface application when the standard fin is used and could be unpredictable in range accuracy.

Because of its background in WAF technology, MICOM led the organization and planning of a wind tunnel test (Reference 2) conducted by the Navy at the NASA AMES Research Center 6x6 trisonic wind tunnel. Detailed analyses of these data were made by MICOM and some of these data are described in Reference 3. The earlier predictions of the MK66 aerodynamic roll moment characterization was substantiated by results of this test and follow-on flight test (References 3 and 4).

This report, in addition to describing the baseline MK66/HYDRA 70 aerodynamic characteristics, provides the technical basis for the unique MOD 1 WAF configuration and defines the aerodynamics that affect rapid roll reversal.

TABLE 1. Physical Characteristics of 2.75 Inch Rockets With MK66 MOD 1 Motors

Configuration	Weight (Lbs) War-head	Weight (Lbs) Motor + Whd Live	Weight (Lbs) Motor + Whd Fired	Length (In)	C.G. From Base (In) Live	C.G. From Base (In) Fired	Moments of Inertia (Lb-In2) Live Axial	Moments of Inertia (Lb-In2) Live Trans-Verse	Moments of Inertia (Lb-In2) Fired Axial	Moments of Inertia (Lb-In2) Fired Trans-Verse
MK 66 Motor Only	---	13.65	6.43	41.750	18.89	15.70	15.80	2032	9.30	1371
M423 PD/M151 HE/MK66	9.30	22.95	15.73	55.125	29.96	33.55	26.20	6248	19.70	5008
M433 RS/M 151 HE/MK66	10.20	23.85	16.63	56.500	30.75	34.52	25.90	6706	19.70	5337
M261/XM267 MPSM/MK66	13.50	27.15	19.93	66.100	35.26	40.02	29.40	9868	23.30	7595
M259 SMOKE/MK66	8.80	22.45	15.23	64.700	31.36	35.80	24.60	7746	17.90	6232
M257 FLARE/MK66	10.57	24.22	17.00	70.400	34.75	40.04	27.60	10607	21.70	8383
PIP M257 FLARE/MK66	9.00	22.65	15.43	69.260	32.75	37.64	25.80	9339	19.90	7579
XM264 SMOKE/MK66	8.00	21.65	14.43	66.100	30.84	35.11	23.70	7639	17.00	6209
XM262 FLARE/MK66	9.00	22.65	15.43	66.100	32.00	36.00	25.80	8000	19.90	6500

TABLE 2. MK66 Thrust And Torque Tables

Time Sec	Thrust lb Force	Torque inch-lb
0.000	0.0	0.0
0.012	1304.3	39.1
0.037	1400.0	42.0
0.062	1439.1	43.2
0.187	1245.7	37.4
0.412	1189.0	35.7
0.437	1267.2	38.0
0.462	1276.9	38.3
0.487	1451.8	43.6
0.512	1457.7	43.7
0.537	1267.2	38.0
0.562	1234.0	37.0
0.862	1522.2	45.7
0.887	1485.0	44.6
0.912	1611.1	48.3
0.937	1654.1	49.6
0.962	1780.1	53.4
0.987	1792.8	53.8
1.037	1463.5	43.9
1.062	1070.8	32.1
1.087	491.4	14.3
1.112	146.6	4.4
1.150	0.0	0.0

Total Impulse to Match Radar Tracking Ballistics Through 1981

Ambient = 1480 Lb-Sec
-30 F = 1466 Lb -Sec
+150 F = 1504 Lb-Sec

II. PHYSICAL DESCRIPTION

The HYDRA 70 rocket system has numerous warheads that may be physically mounted to the MK66 motor. Most of these were developed and fielded with the older MARK 4 and MARK 40 motors. Two basic aerodynamic configurations are more prominent; those similar to the M151 high explosive (10 lb head) and those similar to the M261 submunition head. Table 3 shows several of the more popular variants with their physical differences. The Army tactical fire control system computes fire solutions for the M151 and M261 heads as well as others.

Figure 1 shows an outboard profile of the aerodynamic configuration for the MK66 with both the M151 and the M261 warheads. Figure 2 shows more detail of the MOD 1 wraparound fin. Three WAF's are mounted on pins to the nozzle assembly (at zero incidence) and can be folded inside the nozzle assembly external circumference while in the launch tube. A preloaded spring forces the fins outward while the convex side rides on the inner tube surface during launch. At tube exit the three fins are free to erect in a clockwise rotation and lock open to a position having the tip and root along body radii (see Fig. 3). The rectangular fin projected planform is more than adequate for aerodynamic stabilization. In addition to aerodynamic stabilization of the rocket, even though at zero incidence, a WAF produces an inherent aerodynamic roll moment (References 3 and 4). WAF forces are generally directed toward the fin center of curvature at subsonic speeds and in the opposite direction at supersonic speeds. This means a counter-clockwise, CCW, self-induced aerodynamic roll moment for subsonic flight and clockwise, CW, moment for supersonic flight for the MK66 as shown in Figure 11. Fin leading edge of Figure 2, is beveled at 10.0 deg only on the convex side to generate high aerodynamic roll moment at supersonic speeds in the counter-clockwise direction. The small 10 deg bevel on the trailing edge concave side is to assist in maintaining counterclockwise roll moment at low transonic and subsonic speeds. These bevels were add-ons to overcome the MOD 0 fin roll moment deficiency and to tailor the rocket roll rate during flight to satisfy all warhead, fuze arming, and performance requirements.

The fluted nozzle produces roll torque to create approximately 10 Hz rocket spin rate at launch, tube exit. This is adequate for reduction of system error caused by any thrust vector misalignment. However, motor torque continues to accelerate the rocket roll rate until equilibrium with aerodynamic roll moment is reached. Table 2 shows MK66 axial thrust and roll torque versus burn time (Ref. 5) showing a total impulse of 1480 lb-sec. Data presented in Reference 1 show the total impulse to be 1515 lb-sec based on recent lot sample test results. The 10.0 deg asymmetrical leading edge bevel is designed to retard the boost spin rate safely below fuse arming limitations of ±50 Hz maximum. A second benefit of the leading edge bevel is that during supersonic flight, the rocket is rapidly de-spun from high (30 to 35 Hz) clockwise roll rate to a counterclockwise roll rate within approximately one second following booster burn out as shown in Figure 4. In addition to an upper limit restriction, it is desirable to have less than ±30 Hz for the M261 submunition warhead at dispense event. At low transonic and subsonic rocket speeds ($t > 6$ sec), the leading edge bevel loses most of its effectiveness, and the trailing edge bevel takes control augmenting the inherent WAF roll moment to maintain an approximate 20 Hz counterclockwise spin rate (see Fig. 4). The roll moment of the WAF in itself is not sufficient to keep

TABLE 3. 2.75 Inch Rocket Components

WARHEADS

Identification	Type	Aerodynamic Shape
M151	HE	1
M261	MPSM	2
M259	Smoke	2
M257	Illum(Flare)	3
XM262/263	Illum	2
XM264	Smoke	2
M267	MPSM/Practice	2
M224	Smoke/Practice	1
M229	HE	1
M247	HEPD	1
WDU 4A/13A	Flechette	2
XM255	Flechette	2

FUZES

M433	RS/Multi Option
M439	Elect,Var Time Delay
M423/M427	Point Detonating
M440	Point Detonating
M438	PIBD
WDU 4A/13A	Flechette (Integral W/Whd)
M429	Proximity

NOTES: (Aerodynamic Shape)

1 - Nose shape of M151, see Figure 1

2 - Nose shape of M262, see Figure 1

3 - Blunt Cylinder

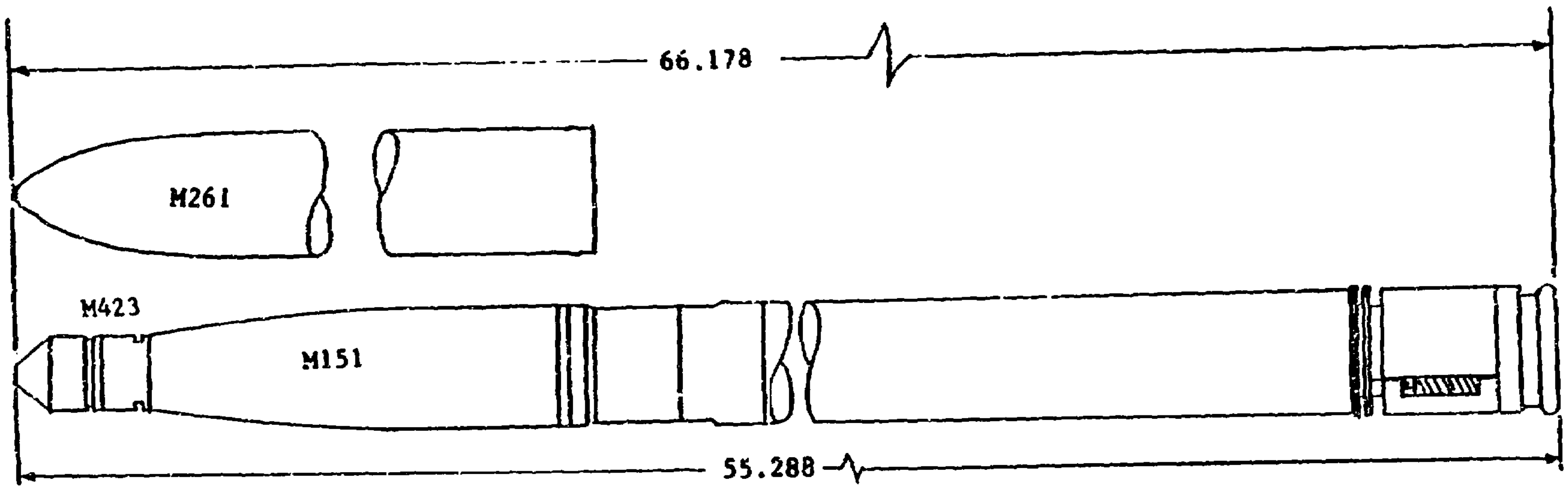


Figure 1. MK66 rocket assembly.

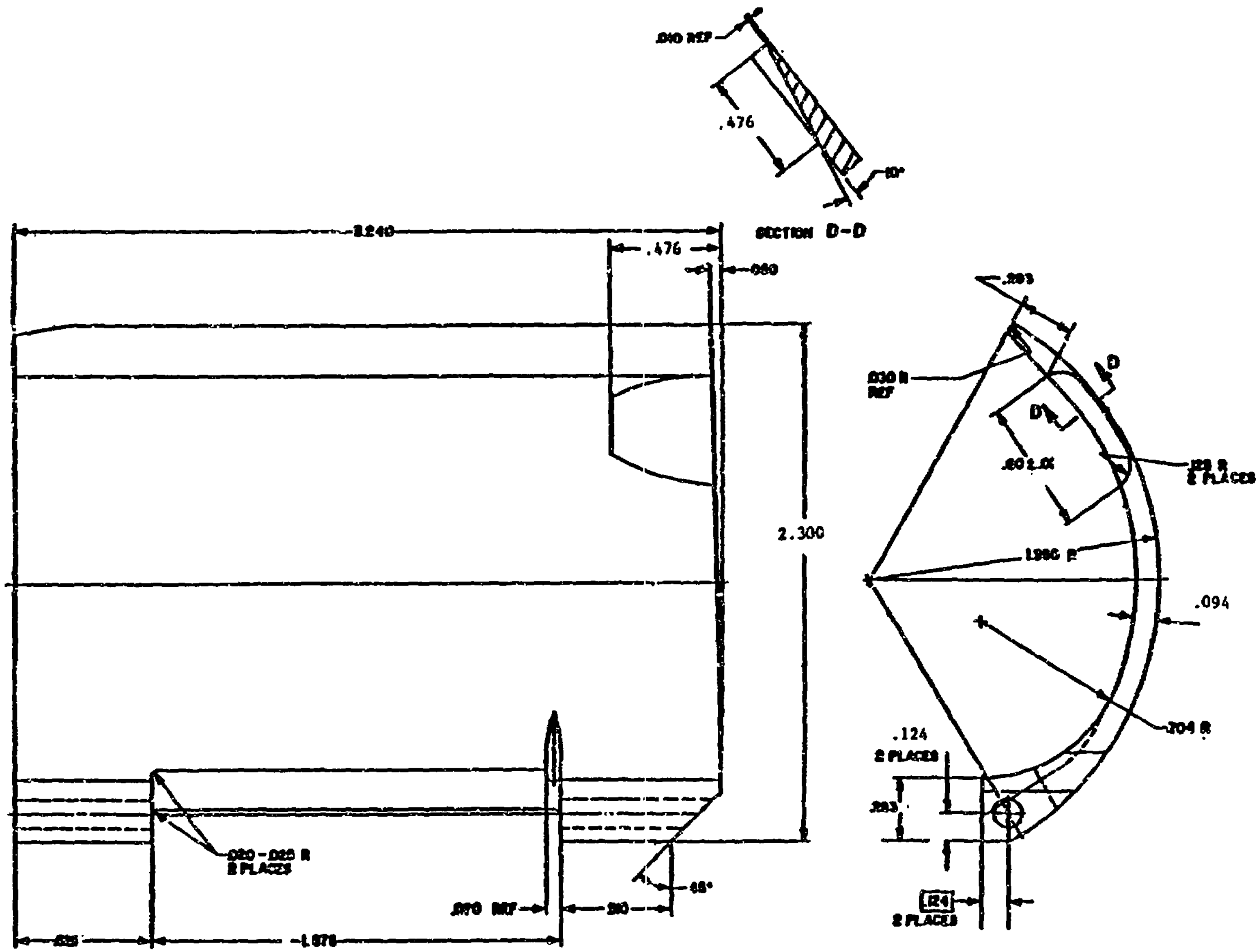


Figure 2. Wraparound fin Mod 0 and Mod 1.

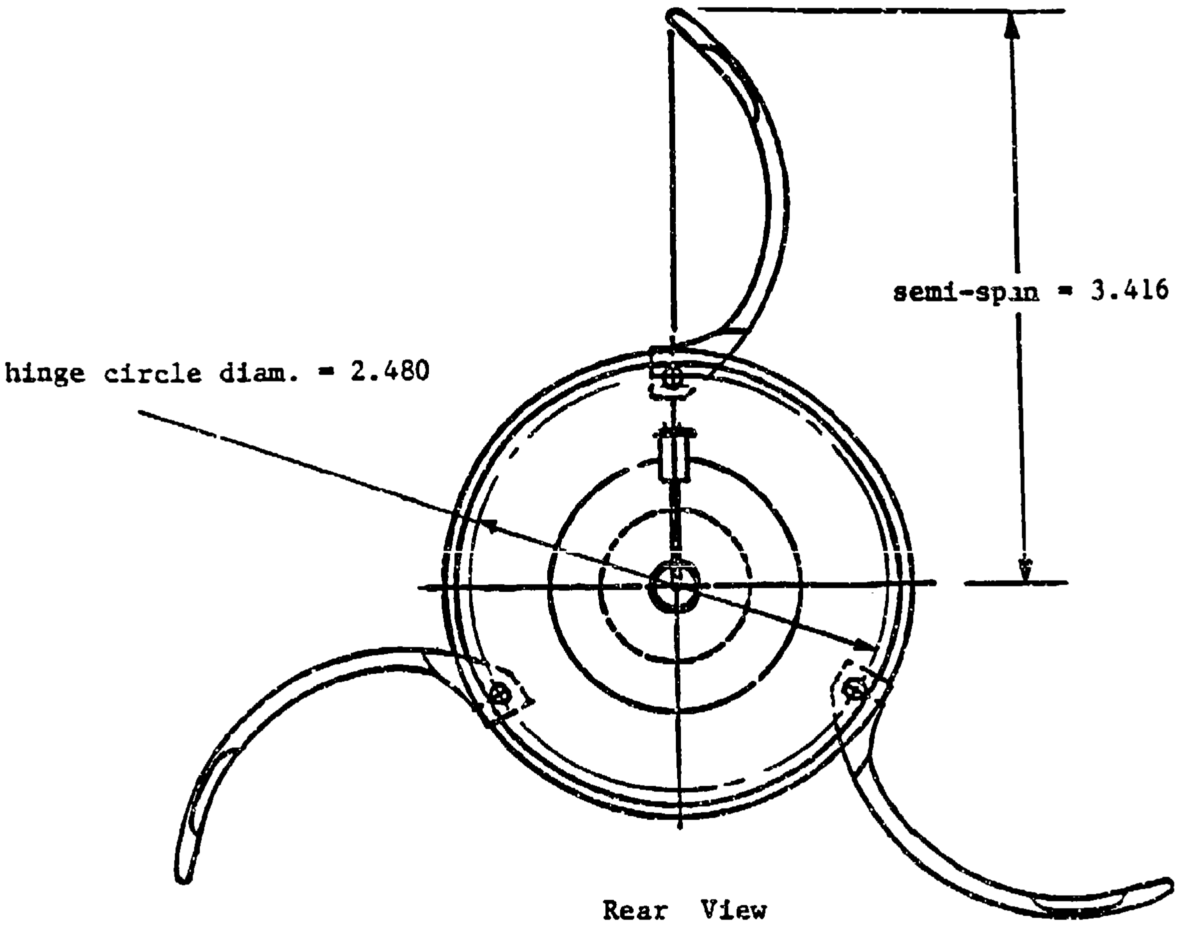


Figure 3. Fin orientation.

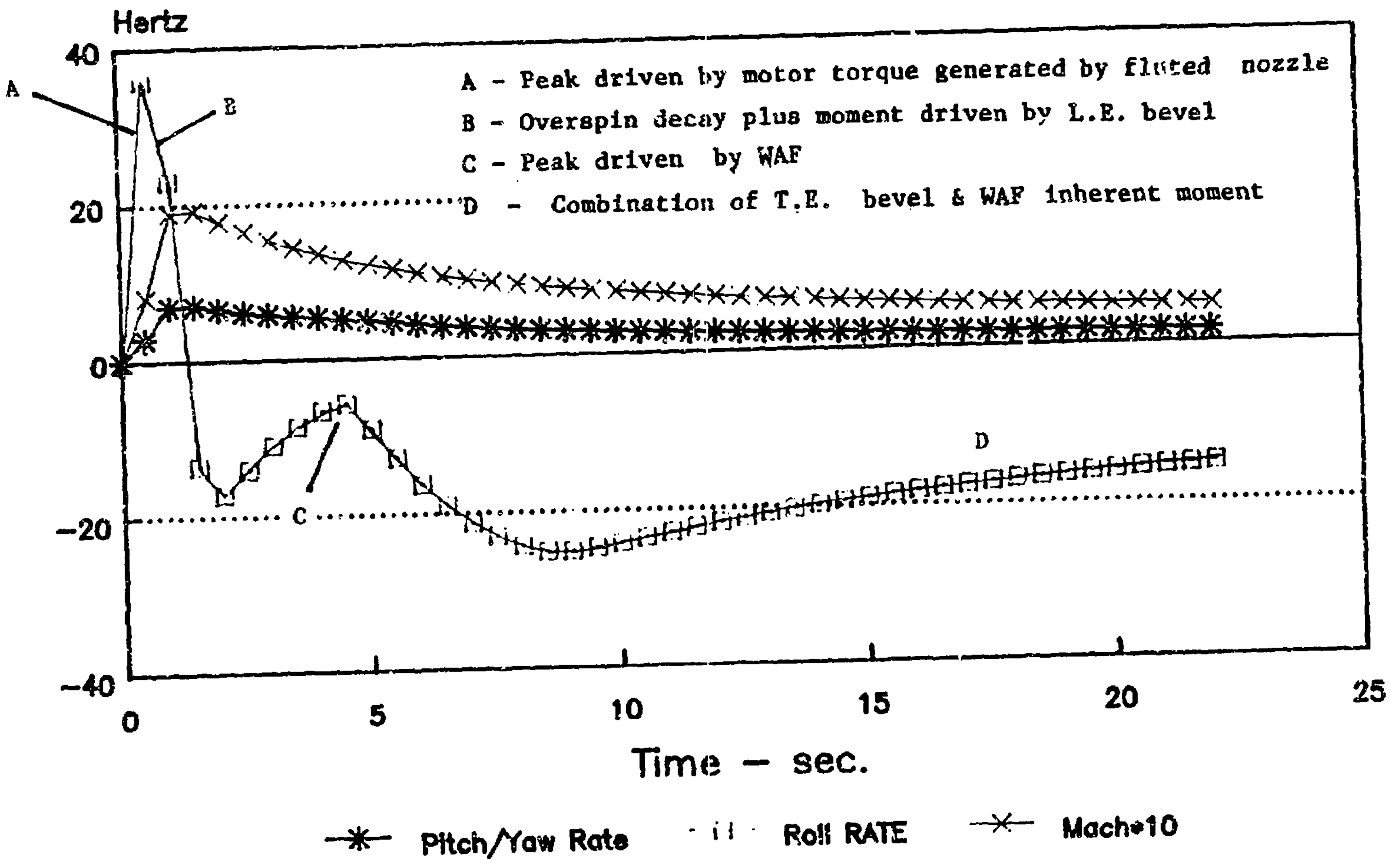


Figure 4. Typical MK66 roll pitch/yaw and Mach history.

the roll rate out of the pitch-yaw natural frequency band. Flight data has revealed that the rocket has a nose down pitch rate of 0.2 rad/sec bias and a ±0.16 rad/sec standard deviation at tube exit. This bias value is included in the fire control algorithm.

III. AERODYNAMICS

This section is meant to show the aerodynamic characterization of the two basic HYDRA 70 aerodynamic configurations (MK66/M151 and MK66/M261) and explain how they were obtained with particular emphasis on the aerodynamic rolling moment coefficients. This is discussed in three parts according to the method of definition. Drag coefficients were obtained almost entirely from flight analysis; aerodynamic stability is derived from wind tunnel data; and the rolling moments were determined from a combination of analytical estimates backed up with wind tunnel test data and verified by limited flight test. Values for the aerodynamics used in the Fire Control Solutions are shown in Tables 4 through 6, obtained from Reference 5.

A. Drag Coefficients

The drag coefficients shown in Table 6 are also shown in Figure 5 for the MK66/M151 and MK66/M261 for both power-on and power-off throughout the Mach number range. The reference area for these coefficients are based on the rocket motor cross-sectional area where D=2.75 in (70 mm). Results from the fire control system reflect these values. Power off was derived from flight data analysis of the coast flight phase, and power on is constructed for an estimated base pressure drag adjusted so that the simulated maximum velocity matches flight data. These data were provided by Armament Research and Development Command (ARDEC) Picatinny Arsenal, Dover, New Jersey. Recent analysis of firings at MICOM Research, Development, and Engineering Center (RD&EC) show that the M151 coast drag may be high by as much as 10 percent.

B. Aerodynamic Stability

A wind tunnel test of the MARK 66 was conducted at the U.S. Army 6x6 Trisonic tunnel located at the NASA AMES facility during the Jan-Feb 1981 time frame. RD&EC assisted in planning and provided the scheduling arrangements with NASA for this test. The Navy provided model parts and engineers to conduct the test. This test was conducted primarily for the purpose of verifying the RD&EC findings related to the early design MK66 roll rate problems. Reference 2 is the Navy data report covering this test, however, analyses for these results were conducted to some degree at both RD&EC and Indian Head. While the AMES test results were adequate for the primary goal of defining roll characteristics, these results would have been deficient for defining static margin. The number of data points were inadequate for a rigorous stability analysis. Shock reflections were suspected of affecting data at some transonic Mach numbers, and 3-fin anomalies can cause confusion. A reasonable definition of aerodynamic center of pressure is all that is required because of the large rocket static margin. The aerodynamic static stability data shown in Table 4 was

TABLE 4. MK66 Aerodynamic Stability Coefficients

MK66/M151				MK66/M261/M264			
Mach	CNa 1/rad	Xcp calibers from Nose	CMq 1/rad	Mach	CNa 1/rad	Xcp calibers from Nose	CMq 1/rad
0.00	8.19	13.39	1060	0.00	8.42	16.53	1740
0.60	8.19	13.30	1060	0.60	8.42	16.53	1740
0.75	3.31	13.53		0.75	8.71	16.71	
0.90	8.94	13.86	1460	0.90	9.05	16.92	1880
1.00			1415	1.00			2140
1.10			1400	1.10			2180
1.15	9.34	14.50	1385	1.15	10.83	17.21	2180
1.30	8.88	14.52	1193	1.30	9.40	17.02	2160
1.45	8.37	14.12		1.45	8.94	16.90	
1.60	8.14	13.85	1069	1.60	8.77	16.82	2000
1.90			970	1.90	8.48	16.68	1880
2.00	7.79	13.57		2.00			
2.20			900	2.20			1770
2.29	7.62	13.46		2.29			
2.48	7.51	13.41	850	2.48			
2.50				2.50			1670
2.67	7.39	13.36		2.67			
2.97	7.22	13.36	800	2.97	8.080	16.41	1570

NOTE: Blank Spaces Due to Different Data Tables
Reference Area = $\pi D^2/4$; D ref = 2.75 Inches (1 Caliber)

TABLE 5. MK66 Aerodynamic Roll Moment Coefficients - All Warheads

Mach	Cl Total	$C_{l\delta}$ 1/rad	Clp 1/rad
0.00	-0.116	2.92	-5.60
0.60	-0.116	2.98	-6.10
0.90	-0.122	3.09	-6.40
1.00	-0.104	3.21	-6.90
1.10	-0.083	3.49	-7.80
1.15	-0.068	3.67	-8.05
1.30	-0.019	4.01	-8.15
1.60	-0.036	3.90	-8.00
1.90	-0.052	3.49	-7.60
2.20	-0.056	3.09	-7.10
2.50	-0.060	2.81	-6.70
3.00	-0.065	2.29	-6.00

Reference Area = $\pi D^2/4$; Ref Dia = 2.75 Inch

TABLE 6. MK66 Drag Coefficients

MK66/M261/M264

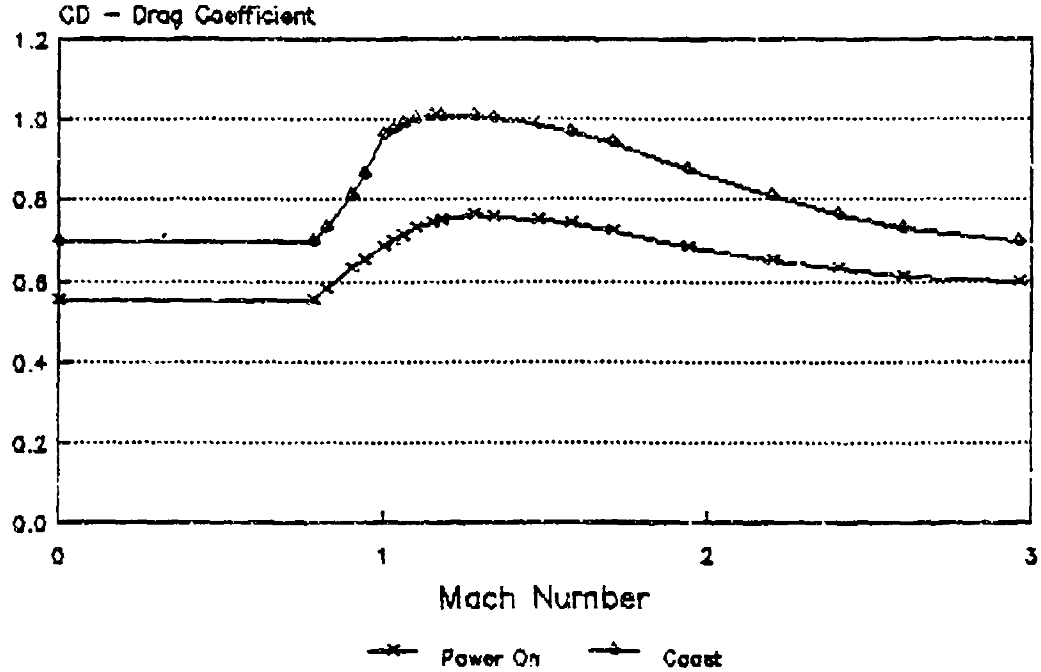
Mach	Power On	Coast
0.00	0.473	0.680
0.68	0.473	0.680
0.70	0.455	0.660
0.74	0.411	0.610
0.76	0.411	0.610
0.79	0.429	0.630
0.90	0.500	0.740
0.95	0.508	0.790
1.00	0.515	0.830
1.05	0.522	0.865
1.10	0.551	0.890
1.15	0.574	0.910
1.22	0.591	0.920
1.30	0.598	0.920
1.40	0.589	0.905
1.50	0.580	0.885
1.60	0.571	0.865
1.70	0.556	0.840
1.80	0.537	0.810
1.90	0.513	0.775
2.00	0.500	0.745
2.10	0.480	0.710
3.00	0.330	0.450

MK66/M151

Mach	Power On	Coast
0.00	0.550	0.700
0.78	0.550	0.700
0.82	0.576	0.730
0.90	0.629	0.809
0.94	0.650	0.863
1.00	0.685	0.960
1.03	0.699	0.977
1.06	0.710	0.989
1.10	0.727	1.000
1.15	0.742	1.008
1.18	0.747	1.010
1.28	0.760	1.012
1.34	0.757	1.005
1.48	0.753	0.990
1.58	0.742	0.970
1.71	0.724	0.940
1.94	0.681	0.875
2.20	0.650	0.811
2.40	0.628	0.765
2.60	0.612	0.730
3.00	0.600	0.700

Reference Area = $\pi D^2/4$; Where D = 2.75 Inches

MK66/151



MK66/261

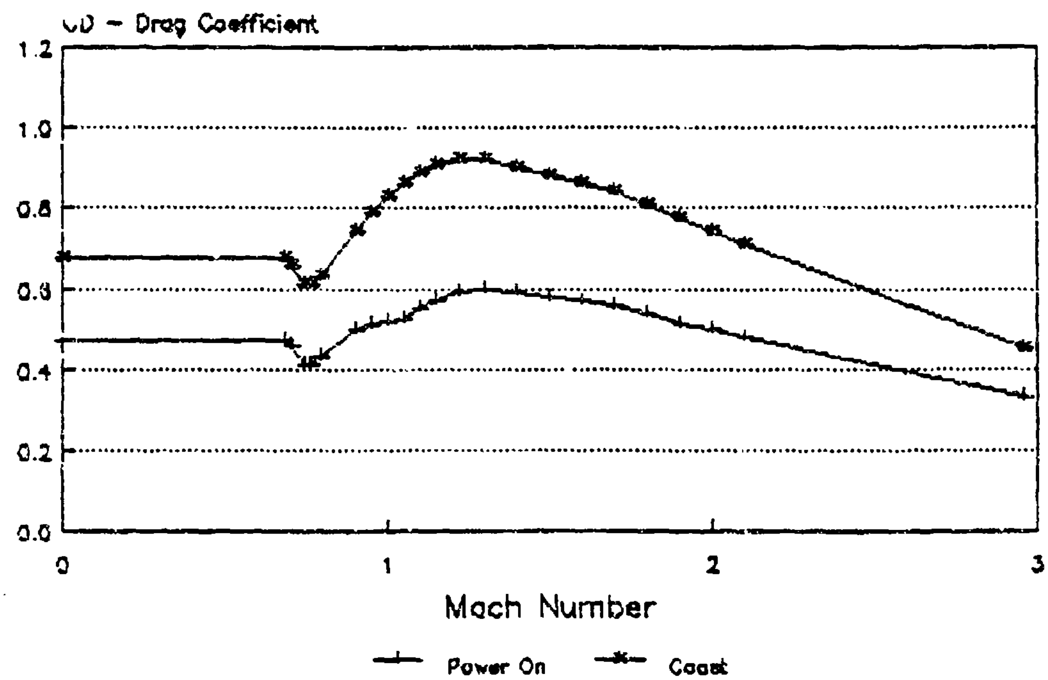


Figure 5. Drag coefficients.

provided by Indian Head based on linearization of these data. Plots of the normal force and center of pressure are shown in Figures 6 and 7. Particularly important is the static margin shown in Figure 7 to be 5 to 6 calibers (body diameters) at the worst case near rocket motor burn out. This rocket is very stable and therefore very sensitive to cross winds. The MICOM analysis of linearized aerodynamic center of pressure (see Fig. 8) is slightly different, but these differences are not significant as far as the fire control solution is concerned because of this large static margin. The RD&EC computation of aerodynamic pitch/yaw damping is used in the fire control solution. This was estimated from a simplified slender body theory approach based on the body and tail fin terms and was computed as follows:

$$CMq = -2[CN\alpha b(Xcpb-Xcg)^2+CN\alpha t(Xcpt-Xcg)^2]$$

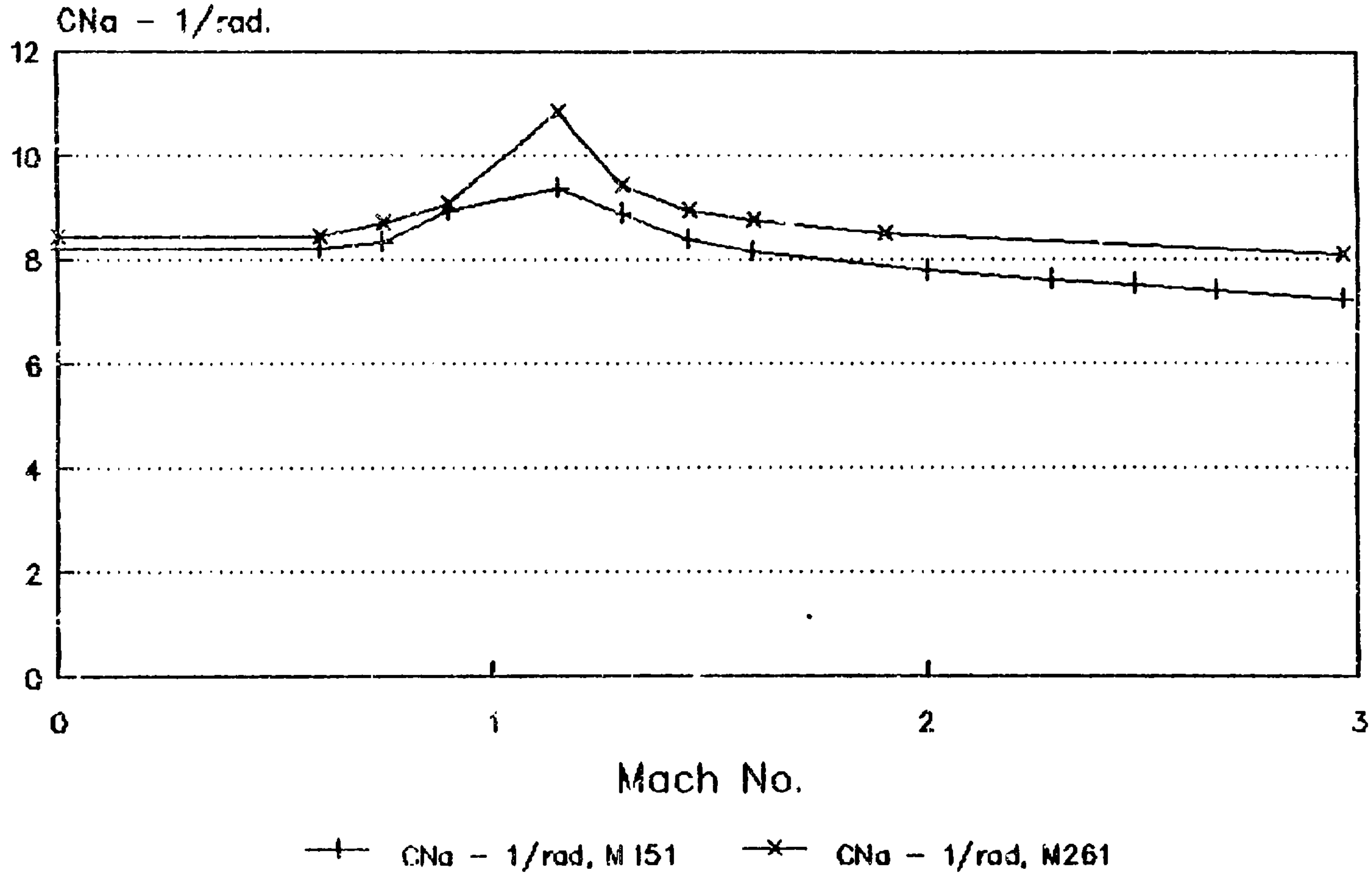
where subscripts "b" represent the body, "t" the tail, and "Xcg" is the center of gravity of the total rocket assembly less the propellant (burnout condition) measured from the same reference point as the Xcg. Results of this calculation are shown in Figure 9.

C. Roll Moment

The original MK66 MOD 0 fin had the same planform as the current MOD 1 fin. It has a symmetrically beveled leading edge and a blunt trailing edge. Early flights revealed range reduction and performance uncertainty. Flight analysis using conventional drag and motor adjustments were unable to produce reasonable solutions for the range anomalies. It had been suggested that erratic rocket wobble (or coning) was the basis of the problem, and that the wraparound fin was the root cause of the wobble. A RD&EC aerodynamic technology program dealing with the wraparound fin had been completed by this time and summarized in Reference 4. The HYDRA 70 Management Office requested that an independent analysis of the problem be made by MICOM RD&EC.

Wraparound fins were mounted on two different rocket afterbody configurations during the aerodynamic technology study. One had a step down beginning at the fin leading edge with the wraparound simulated hinge mounted in this step down portion, and the other had the fins mounted on the maximum diameter straight body surface. Two important results of the wraparound fin study were: (1) the wraparound fin self-induced aerodynamic roll moments may, and usually will depending on planform, change direction near or at Mach = 1.0; and (2) may change direction a second time in the low supersonic Mach number range if mounted on an afterbody that steps down to a smaller diameter where the fins are mounted.

As shown in Figures 1 and 3, the MK66 motor has a recessed zone where the fins are hinged similar to the step down in Reference 3, except there is a raised portion behind the fins, making the fin hinge totally enclosed in a recessed zone. Initial estimates from empirical analysis of the wraparound data applied in the MK66 geometry modeled the aerodynamic roll moment using both smooth and step down body trends. These estimates were used to simulate the MK66 roll rates, and were compared to typical flight results (see Fig. 10). This comparison illustrated two points



Aref = pi/4*D^2, D = 2.75in.

Figure 6. <u>MK66 rocket aero normal force coefficients.</u>

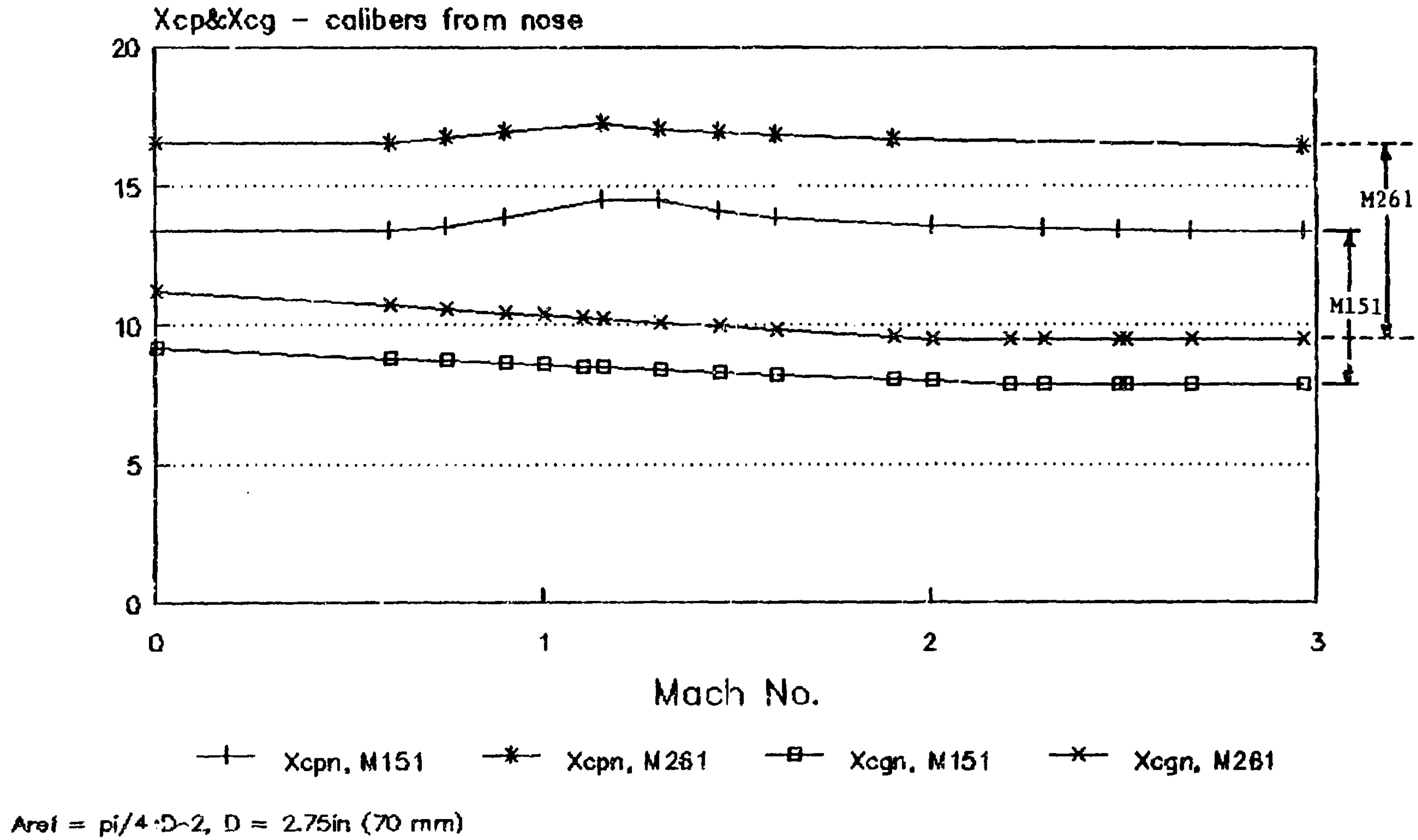
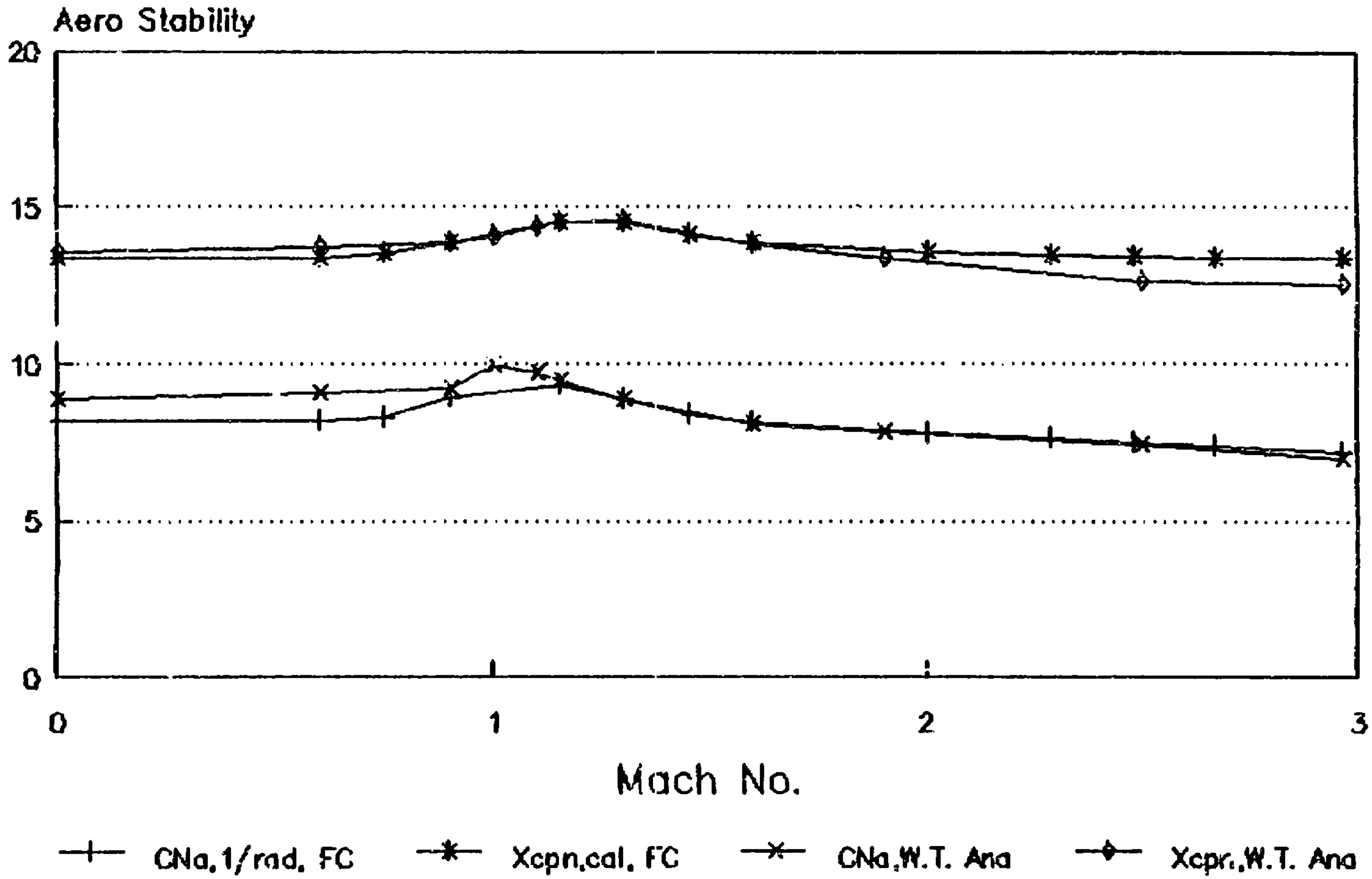


Figure 7. MK66 rocket aerodynamic stability margin.



Aref = pi/4*D^2, D = 2.75in.

Figure 8. MK66 fire control compared to wind tunnel analysis.

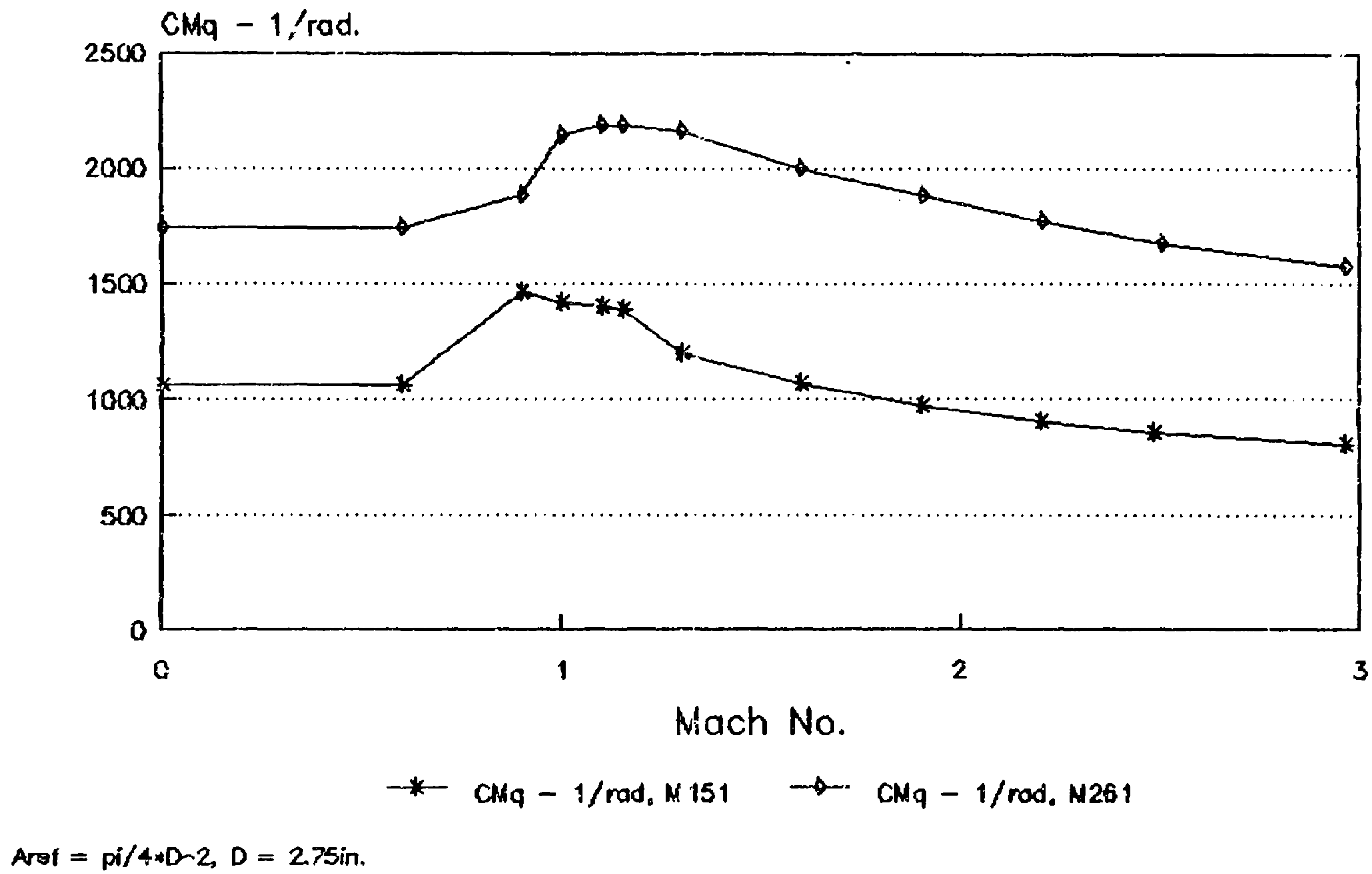


Figure 9. MK66 rocket aero damping coefficients.

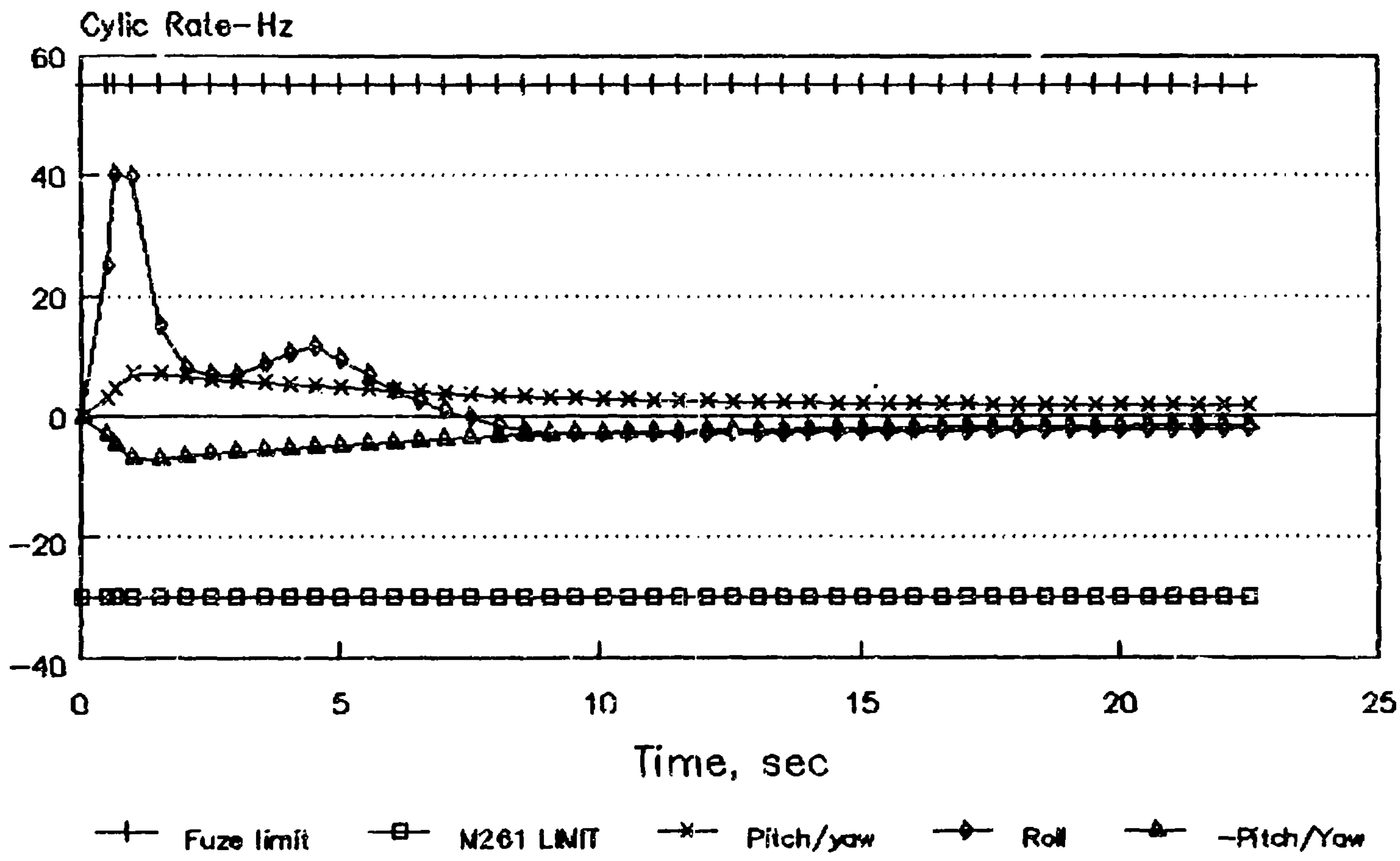


Figure 10. MK66/151 Mod 0 roll and pitch frequency.

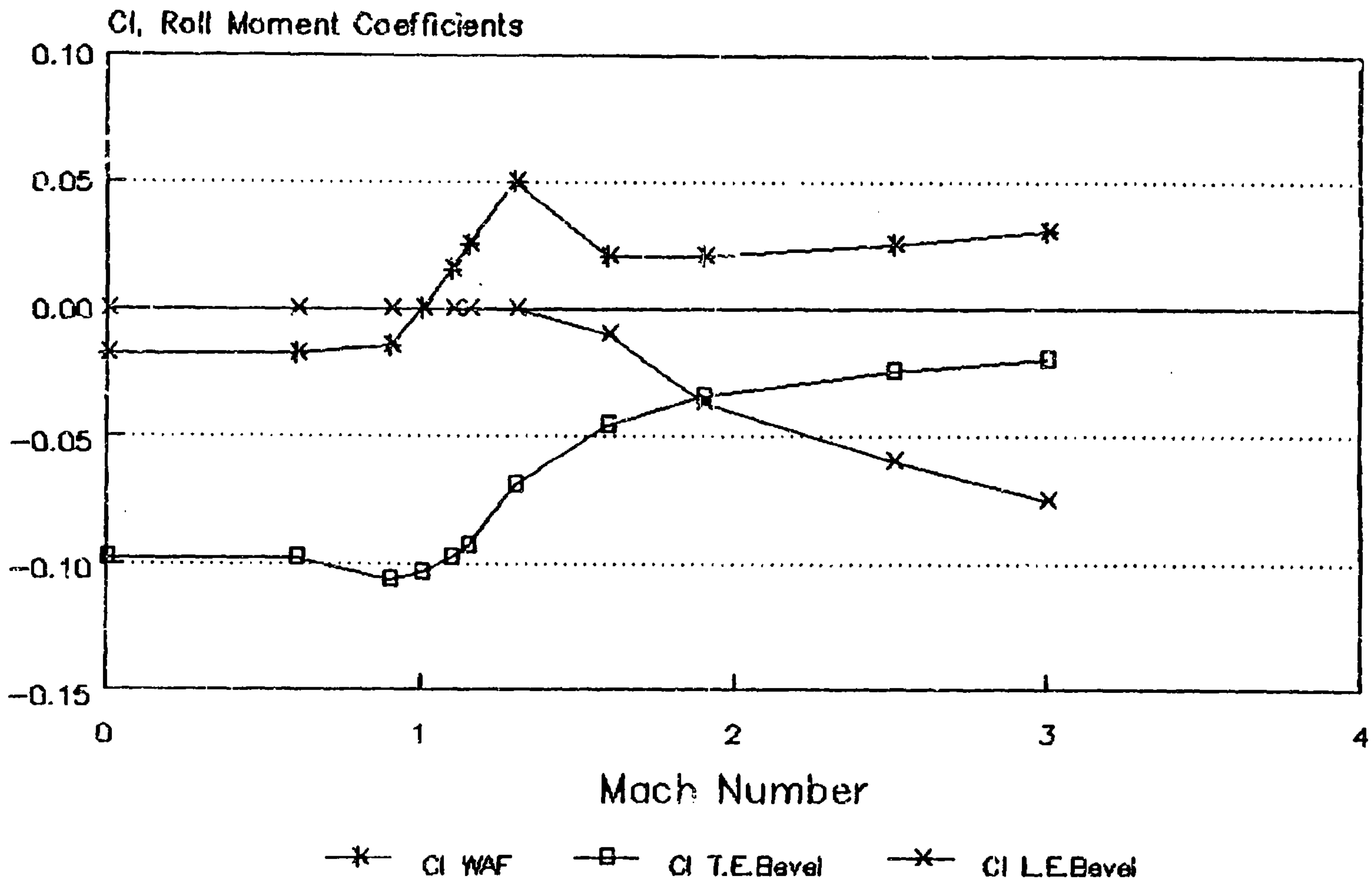


Figure 11. Mark66 aerodynamic roll moment breakdown.

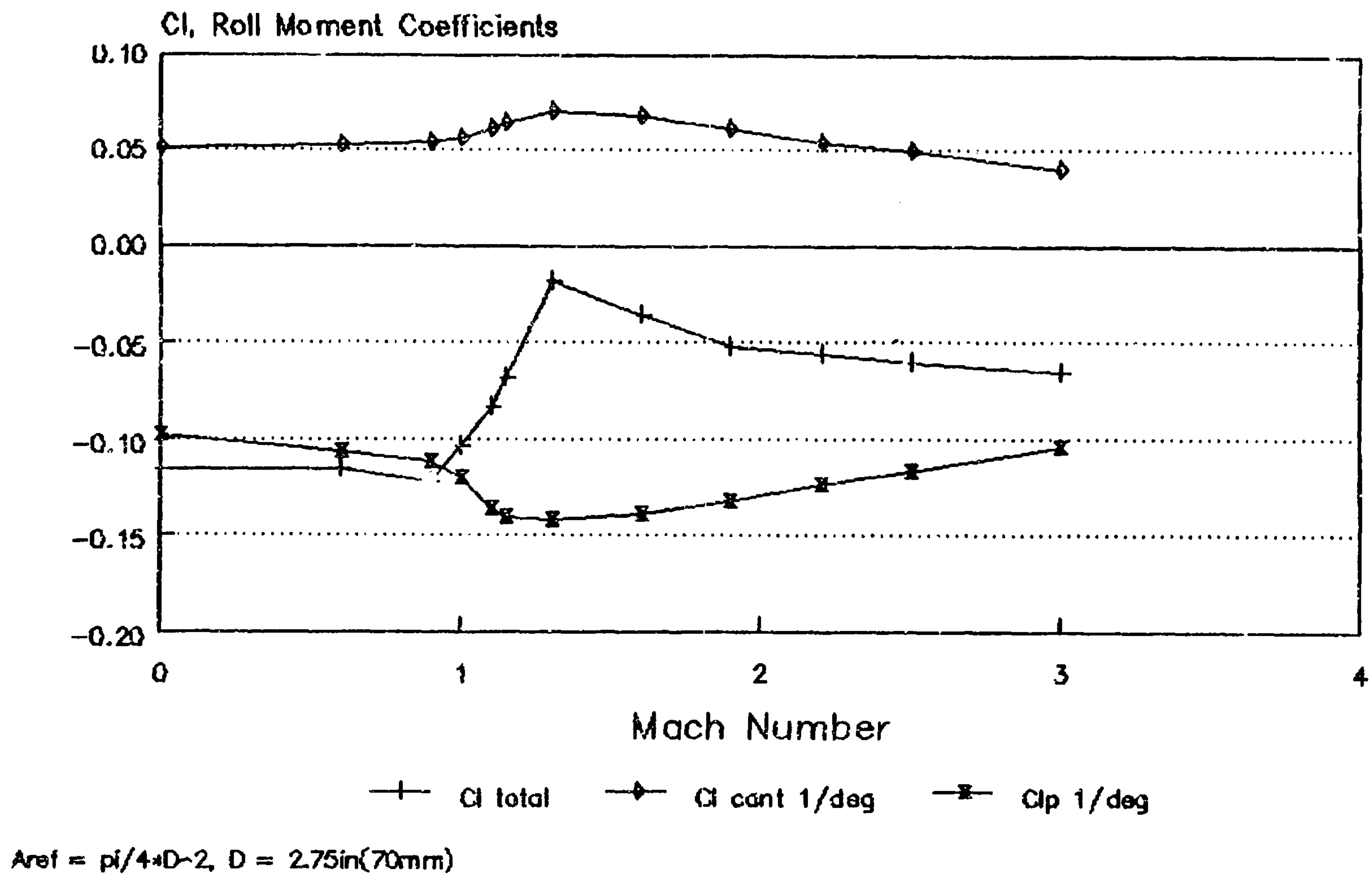
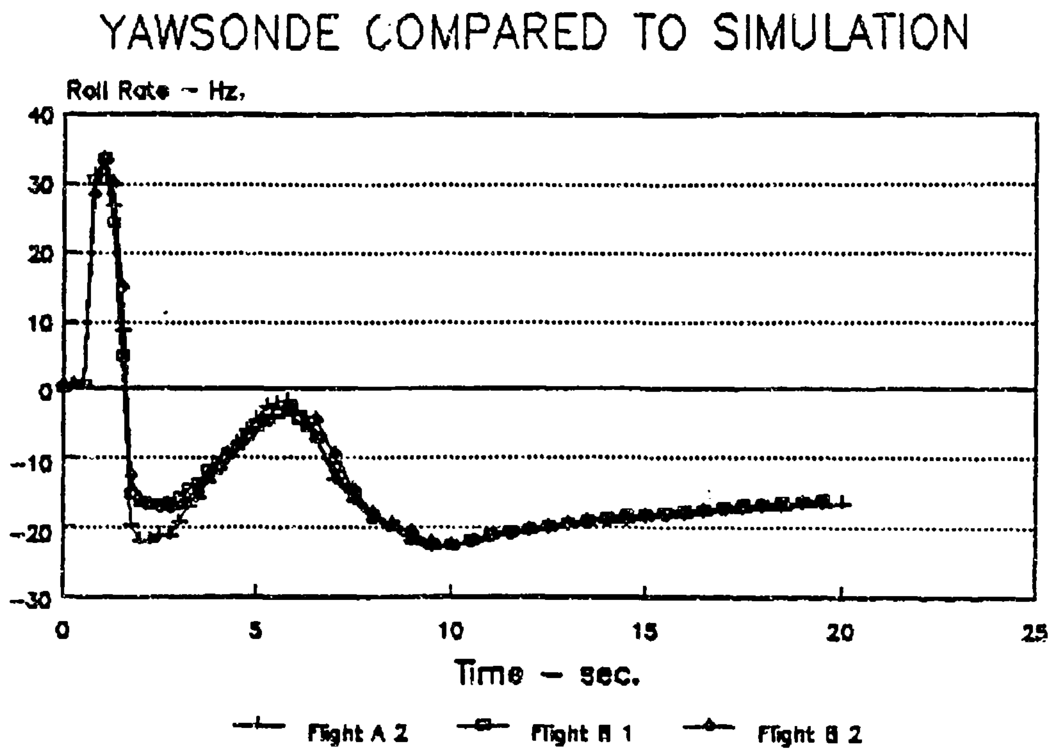


Figure 12. Mark66 aerodynamic roll moment coefficients.



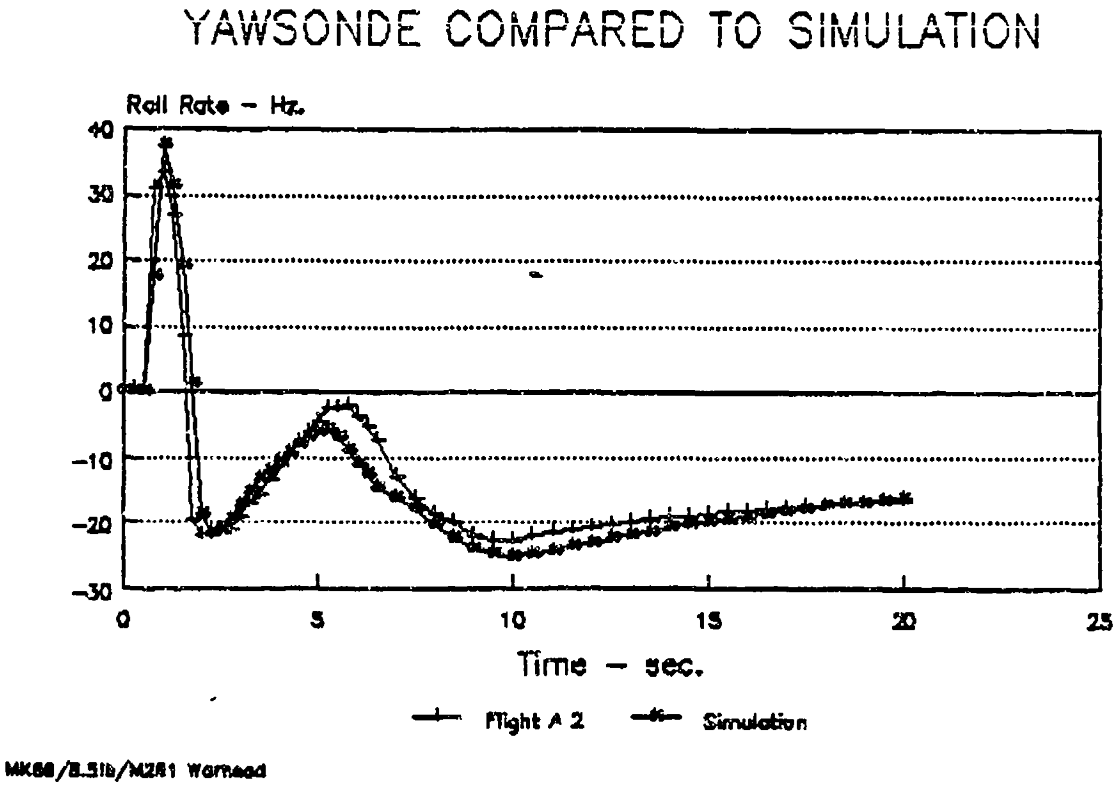


Figure 13. <u>MK66 flight roll rate.</u>

that led to both an understanding and a fix to the range reduction problem: (1) the smooth body trends almost identically matched flight results, and (2) roll rate and the pitch/yaw rates were very close to the same magnitude for an extended period, and rocket wobble could be expected to occur by as early as 5 seconds and certainly after 8 or 9 seconds of flight. This chart shows the MK66 MOD 0 roll rate history over several seconds of flight time along with the pitch/yaw natural frequency band. Also shown are the fuze and warhead limitations that the HYDRA 70 system has with respect to roll rate. There is a ±55 Hz limit on spin rate during boost acceleration for arming of some warhead fuzes and a ±30 Hz limit on spin rate for the M261 submunition warhead at time of munition dispense. In order to avoid wobble, a difference of several cycles per second should be kept between these various periodic motions. The clockwise roll torque from the fluted nozzle continues to accelerate the spin rate through boost until equilibrium with fin aerodynamic roll moment and damping is obtained. Methods investigated that insured rocket clockwise spin stayed above the pitch/yaw rate also increased the boost spin rate near or beyond the arming limit. The asymmetrical leading edge bevel had been investigated during the RD&EC WAF technology study and found to be a strong roll driver at supersonic speeds with little or no roll effectiveness at subsonic speed, while trailing edge tabs and bevels are generally known to be particularly effective as subsonic lift generators. Roll moment and roll rate estimates were made for a number of combinations of bevels and tabs applied to the MK66 MOD 0 fin that sufficiently separated rocket spin rate from the pitch/yaw rates yet remain within the fuze and warhead constraints. The final conclusion arrived at was that a leading edge bevel on the concave side could be used to retard the rocket motor spin during the boost supersonic speeds and allow the rocket to reverse the roll direction while rapidly passing through the pitch/yaw frequency range. A small trailing edge bevel on the convex side would provide the necessary torque to augment the induced WAF roll moment during the remaining subsonic flight. A plot of Mach number and roll rate for a typical MK66 flight is shown in Figure 4 where these various drivers are highlighted. The roll rate history of the MK66 with the MOD 1 fin is controlled by the combining of the WAF, leading edge bevel, and trailing edge bevel aerodynamic roll moment coefficients shown in Figure 11. Motor roll torque dominates during boost while maximum rate is limited by the sum of this torque, the total aerodynamic roll moment, and aerodynamic roll damping. This is shown (Cltotal) in Figure 12 and Table 5. Roll moment due to fin cant or incidence is also shown in Figure 12. However, since the fin is designed to have zero incidence, this effect is only used to study tolerance variances, etc. Aerodynamic damping was estimated using slender body theory and verified through wind tunnel spin data analysis and flight test simulations. The roll moment coefficients in Figure 12 were further confirmed through special dedicated flight test, (Reference 6), results which are shown in Figure 13. Two important notes should be pointed out when reviewing these data: (1) the range timing during the YAWSONDE test flights were not initialized precisely, and (2) a non-tactical 8.5 pound M261 warhead was flown. The time that the rocket exits the launch tube is on the order of 0.08 seconds following motor ignition and has a roll rate at tube exit of approximately 7 Hz for this warhead. An approximate 0.5 second timing shift explains most of this period of 0.64 sec with zero roll rate. Also shown in Figure 13 is a comparison to simulation of the MK66/8.5 lb M261

using these coefficients where a 0.5 second shift to the simulation results are applied. The difference between the current MOD 1 and the original MOD 0 fin roll rate histories are illustrated in Figure 14. As can be seen, the MOD 1 satisfies all requirements except for a short dwell time near four seconds. There has not been any indication of rocket wobble since the incorporation of the MOD 1 fin. The difference in rocket spin rate due to the various warheads is exemplified in Figure 15, where the M151 and M261 are compared. As shown, the principal difference is a phase shift caused by the small difference in two configurations ballistics (drag and mass Mach number effect). Comparing these with the simulated roll rates of flight A2 in Figure 13, the effect of roll moment of inertia is illustrated by the overspin differences immediately following roll reversal at approximately two seconds.

IV. SUMMARY

Tables 4 through 6 present the aerodynamic coefficients for the HYDRA 70 MK66 two basic configurations for which the fire control solutions are computed. It should be pointed out that, if significant alterations of the rocket ballistics are made such as propellants, launch conditions or airframe design changes, additional roll rate analysis should be conducted.

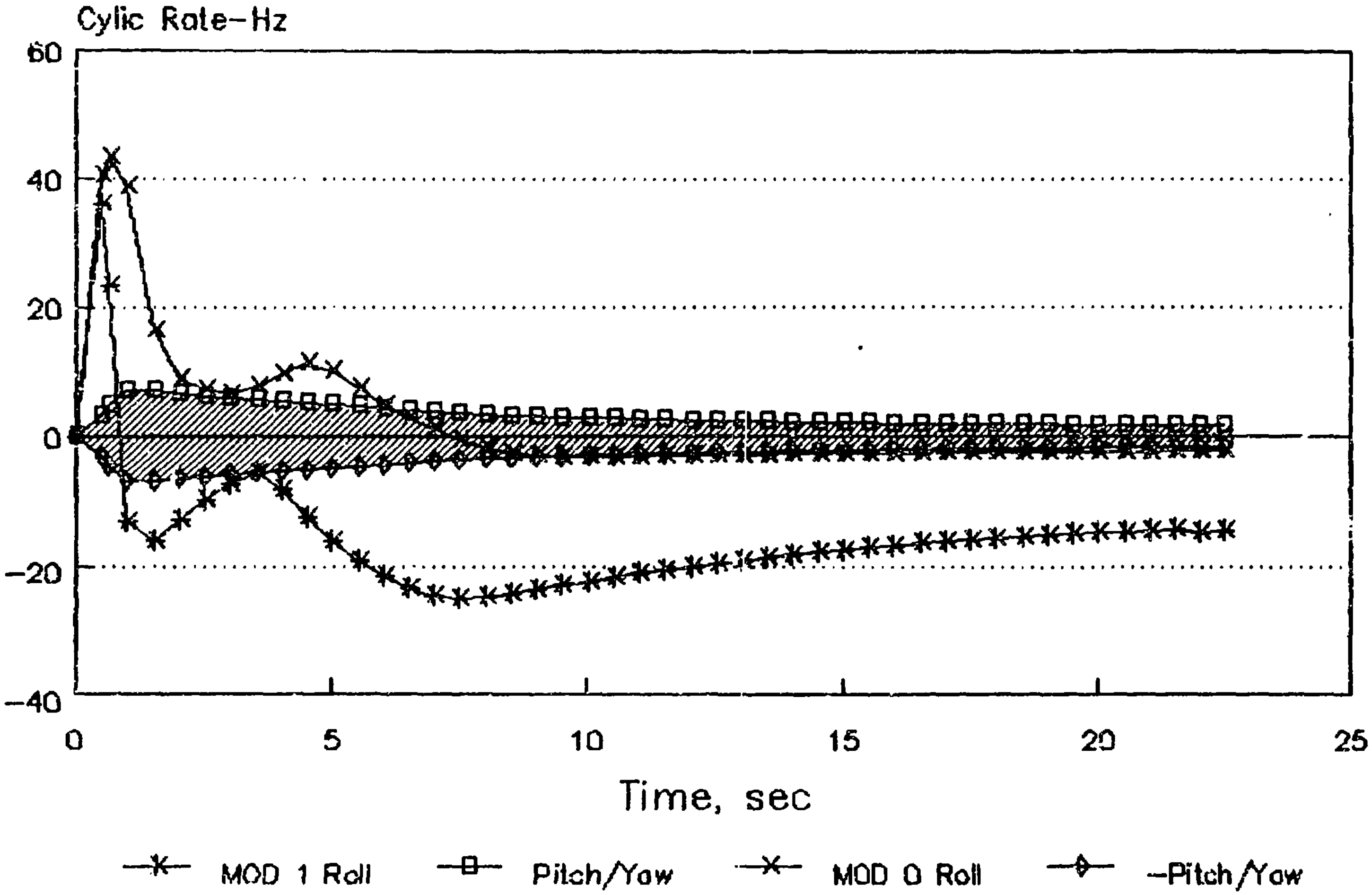
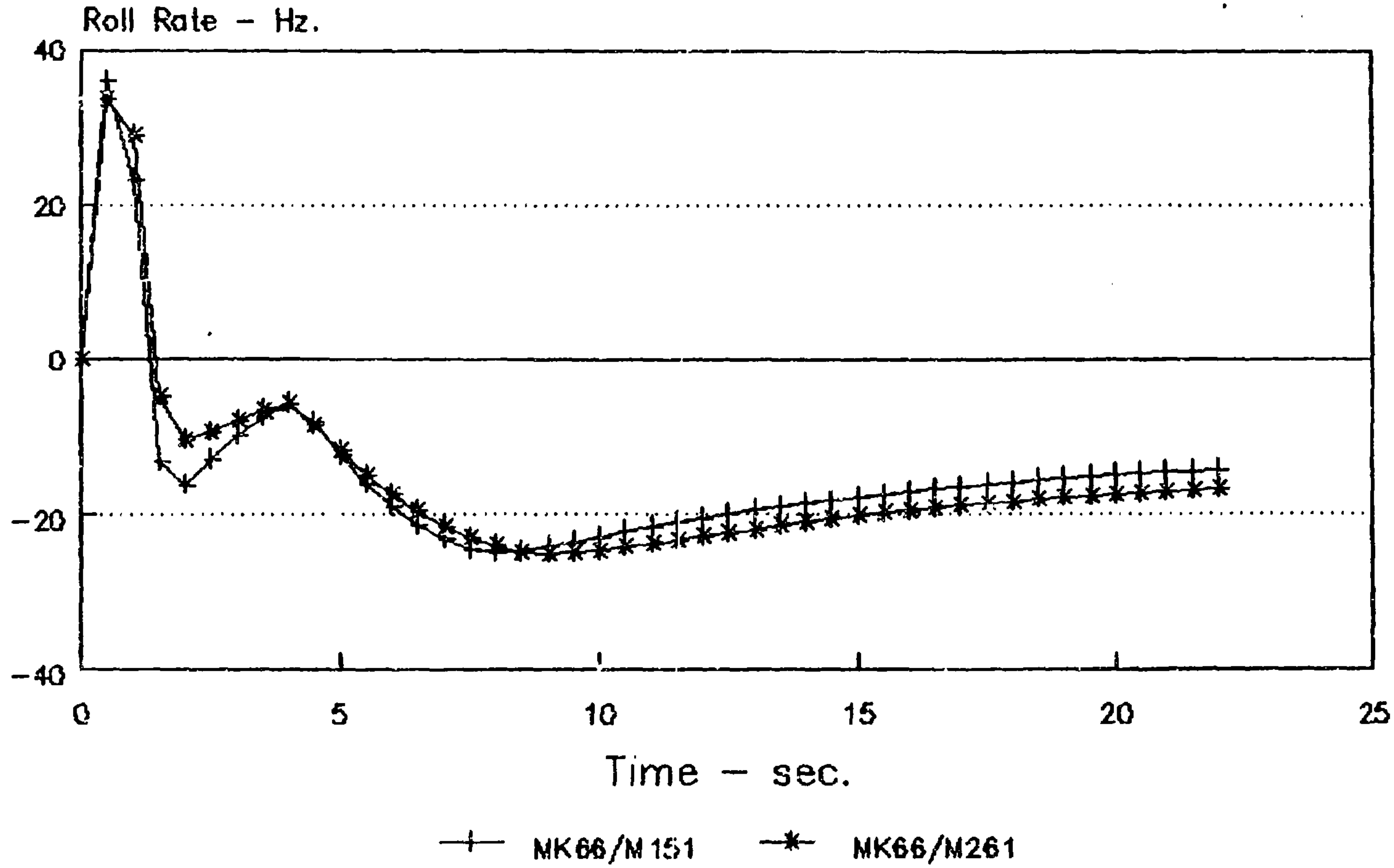


Figure 14. MK66/M151 Mod 1 compared to Mod 0 rollrates.



Q.E = 35 deg.

Figure 15. Roll comparison of M151 and M261 warheads.

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